Journal of Civil & Environmental Engineering

Kader et al. J Civil Environ Eng 2016, 6:4
DOI: 10.4172/2165-784X.1000239

Research Article Open Access

Effect of Bolt-Hole Position Errors on the Strength of Bearing-Type Multi-Row Bolted Connection of FRP Composite Members

Kader MA*, Kitane Y and Itoh Y

Nagoya University, Nagoya, Aichi, JAPAN

Abstract

The aim of the study is to evaluate the effect of bolt-hole position errors on the strength of bearing-type multi-row bolted connections with a double-lap configuration of fiber reinforced polymer composite members. To simulate errors in positioning bolt-holes in the loading direction of connections, the statistical technique of sampling known as Latin hypercube sampling has been adopted in this study. In the Latin hypercube sampling, the distribution is obtained using the results of goodness of fit tests. It has been seen from the goodness of fit tests that the strength of the two- to four-row bolted connections with steel cover plates and two-row bolted connection with FRP cover Plates can be modeled by using the normal distribution and the three and four-row bolted connections with FRP cover plates can be modeled by using the Weibull distribution with a significance level of 0.05. The strength of bolted connections is obtained by performing progressive damage analysis of the connections numerically. The statistical analyses show that the bolt-hole positioning errors have significant effect on the strength of the bolted connections, and that the strength can either increase or decrease with a larger probability to decrease. Connections with steel cover plates are more sensitive to bolt-hole position errors than those with FRP cover plates. Ninety five percent non-exceedance strength of the connection with FRP cover plates is about 85% of the connection with bolt positions perfectly aligned, that of the connection with steel cover plates is about 71% of the perfect bolt position case.

Keywords: Bolt-hole position; FRP composite; Latin hypercube sampling; Bearing-type connection; Progressive damage analysis; Ultimate strength

Introduction

The civil engineering structures made of steel and concrete would deteriorate over time due to various reasons. In order to prevent the deterioration and reduce the life-cycle cost of a structure, the applications of fiber reinforced polymer (FRP) for a structure in a harsh environment may be one of the options. FRP composite materials do not corrode in the severe environment. The materials have other advantages in the context of structural applications such as high specific strength and stiffness, light weightiness, tailored properties, and outstanding fatigue resisting capacity [1]. The materials have been increasingly used in the civil engineering industry for strengthening and construction of structures for a few decades.

Structural members need to be connected properly and adequately to build a reliable and safe structural system. In the civil engineering structure, mechanical fastener connections such as bolted connection provide more advantages than the other connections and are often chosen to connect members. However, a severe stress concentration occurs at bolt holes, and bolted connection of FRP composite members can be a source of weakness [2]. Furthermore, design guidelines of the bolted connection of the FRP members have not been fully developed yet. Therefore, many issues need to be resolved before this advanced material can be fully utilized to provide reliable and efficient connections.

Bolted connections can be of either a friction-critical type or a bearing type. Since strength of a friction-critical bolted connection if FRP structures cannot be determined easily due to creep of the FRP material, bearing-type bolted connections are typically used. Strength of a bearing-type bolted connection depends on the failure mode. Common failure modes in a bolted connection of FRP structures are (a) bearing failure, (b) net-tension failure, (c) shear-out failure, (d) cleavage failure, (e) cleavage-tension failure, and (f) bolt failure. In addition, failure may consist of their combination. Among these failure modes, the bearing failure mode is considered to be a desired mode because it is less catastrophic than other failure modes.

Many researches have been conducted to determine the effect of various parameters on the strength of bolted connections of FRP members [2-12]. These parameters include: (a) connection geometry and plate width to bolt diameter ratio, w/d, pitch distance to bolt diameter ratio, p/d, and end distance to bolt diameter ratio, e/d; (b) connection configuration; (c) stacking sequence; (d) fiber orientation; (e) friction and bolt torque; (f) clearance of hole; and (g) cover plate stiffness.

The present study focuses on the bearing-type multi-row bolted connections with a double-lap configuration of FRP members. Bolts in different rows do not shear the same amount of force due to the relative displacement of the cover plates to the main plate. The load distribution depends on the several factors such as the relative stiffness of the cover plates to the main plate, bolt-hole position and clearance, axial force in the bolt, friction between FRP plates and between FRP plate and washer. For a ductile material, the load distribution among the bolt rows does not affect the ultimate strength of the connection since the load would be re-distributed among the rows of bolts due to the plastic deformation [13]. However, the load distribution in a connection of a brittle material like FRP affects its ultimate strength because the load does not re-distribute among the bolts.

The authors [8,14] investigated the effect of the cover plate stiffness on the behavior of multi-row bolted connection up to four rows of bolts by numerical analysis. The results show that the load distribution among the bolts changes with the change of cover plate's stiffness and that a connection with larger stiffness of cover plate tends to show

---

***Corresponding author:** Kader MA, Nagoya University, Nagoya, Aichi, JAPAN, Tel: +81-52-877-6988; E mail: kader.mohammad.abdul@e.mbox.nagoya-u.ac.jp

Received May 25, 2015; **Accepted** June 25, 2015; **Published** July 05, 2015

Citation: Kader MA, Kitane Y, Itoh Y (2016) Effect of Bolt-Hole Position Errors on the Strength of Bearing-Type Multi-Row Bolted Connection of FRP Composite Members. J Civil Environ Eng 6: 239. doi:10.4172/2165-784X.1000239

lower strength. MaCarthy et al. [7] and Fan et al. [15] investigated the load distribution among the bolts with bolt-hole position error. They investigated the three-row bolted connections with bolt holes perfectly positioned and positioned with an error of 80 μm, 160 μm, and 240 μm for FRP cover plates. They used a nominal hole diameter of 8 mm. The ISO specifies the tolerance of the f7/H10 fitting of 86 μm for 8 mm bolt hole which is in used by European aircraft manufacturer. They showed that the bolt-hole position error affects load distributions among the rows of bolts which may lead to early damage of bolt holes.

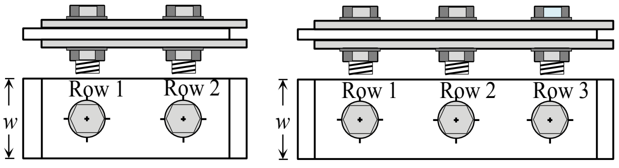
The aim of this paper is to examine how bolt-hole position errors effect the strength of bearing-type multi-row bolted connections with a double-lap configuration of FRP composite members. The bolt-hole position errors are randomly generated by Latin hypercube sampling. Steel and FRP cover plates with a half of the main plate thickness are used in the connections. Progressive damage analyses are performed on the connections with bolt-hole errors to understand the effect of bolt-hole position errors on the strength of the connections with steel and FRP cover plates. A statistical test is conducted on the results to obtain the type of statistical distribution.

Materials and Methods

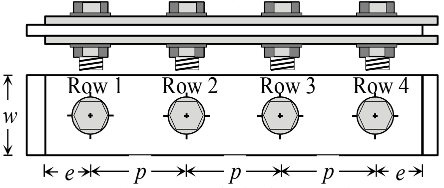
Connection geometry

The bearing-type multi-row bolted connections a double-lap configuration with two, three, and four rows of bolts in a line are examined by finite element analysis, which are shown in Figure 1. The main plate is an FRP plate with a thickness, t_m, of 12 mm. Two types of cover plate material are used: FRP and steel. The thickness of cover plates is 6 mm. Steel bolts with a diameter, *d*, of 16 mm and the bolt-hole diameter, d_h, of 17 mm are used, resulting in a clearance of 1 mm. The clearance changes with the change of bolt-hole position. The bolt-hole position error is described in the next section.

The geometric parameters used in the study are shown in Table 1. The plate width to bolt diameter ratio, *w/d*, is different for connection with a different number of bolts, but the pitch distance to bolt diameter ratio, *p/d*, and the edge distance to bolt diameter ratio, *e/d*, are fixed all connections. Based on the geometry considered in this study, the connections are expected to be bearing failure.



(a) Two-row bolted connection (b) Three-row bolted connection



(c) Four-row bolted connection

Figure 1: Geometry of connections.

Two-row			Three-row			Four-row		
w/d	***p/d***	***e/d***	***w/d***	***p/d***	***e/d***	***w/d***	***p/d***	***e/d***
4.0	4.0	2.0	5.0	4.0	2.0	6.0	4.0	2.0

Table 1: Geometric parameters of connections.

Sampling

To determine the effect of bolt-hole position errors on the strength of bolted connections, the Latin hypercube sampling technique is adopted in this study for simplicity and accuracy. The Latin hypercube sampling was first proposed by McKay et al. [16]. To do a special type of Monte Carlo simulation, Latin hypercube sampling uses the stratification of the theoretical probability distribution function of input random variables. At first, the cumulative probability distribution functions (CPDF) for all random variables are divided into *N* intervals of equal probability and then centroids of intervals are used in the simulation process. The samples can be obtained by using the formula

$$x_{i,k} = F_i^{-1}\left(\frac{k-0.5}{N}\right) \tag{1}$$

where $x_{i,k}$ is the *k*-th sample of the *i*-th variable X_i , F_i^{-1} is the inverse CPDF for variable X_i.

Based on random permutations of integers 1, 2, ... N, the representative parameters of variables is selected randomly. Every interval of each variable will be used only once during the simulation. In this study, fifty simulations are performed for each connection. Therefore, fifty different bolt-hole positions are generated by using the Latin hypercube sampling for each bolt hole and randomly selected for the bolt holes of a connection in which every interval of each bolt-hole position is used only once during the simulation.

To determine the statistical distribution of the bolt-hole position error, 257 bolt holes in a number of connection GFRP plates to be used in the experimental study of bolted connections are measured. The measured data are found to follow a normal distribution with the mean of -0.014 mm and standard deviation of 0.099. The maximum bolt-hole position error is of 0.41 mm. In the study, the bolt-hole position errors are assumed to be normally distributed with a mean value of 0.00 mm and a standard deviation of 0.17 mm for all bolt holes. In the Latin hypercube sampling, 50 intervals are used. To include ± 0.4 mm in the sampling data, which is about the same magnitude as the maximum error found in the measurement, the standard deviation of distribution is set to 0.17 mm in place of 0.099.

Material properties

Quasi-isotropic glass-fiber laminates are used in this study. The stacking sequences of the 6-mm cover plate and the 12-mm main plate are $[0°/90°/\pm45°]_{2S}$ and $[0°/90°/\pm45°]_{4S}$ respectively. The thickness of each ply in the laminates is 0.375 mm. The material properties of unidirectional lamina are given in Table 2. Bolts and plates are of stainless steel, SUS 304, and their properties are shown in Table 3. Stress-strain curve of the stainless steel used in this study is the one specified by Eurocode 3.

Finite element model

Three dimensional finite element models of bolted connections are created in the general purpose finite element software, Abaqus [18]. A quarter of a connection is modeled by taking advantage of symmetric conditions as shown in Figure 2. At the center of the cover plate x-symmetric boundary conditions are defined, and a displacement is applied at the continuous edge of the main plate. Three dimensional solid eight-node elements are used to model FRP composite plates, steel plates, and steel bolts and washers. Washer and bolt are modelled together as a single part. The element size near the bolt hole about 0.75 mm × 1.5 mm × 3.0 mm, and that of the other portion is about 1.5 mm × 2.0 mm × 3.0 mm. The thickness of element is divided into 8 layers

Citation: Kader MA, Kitane Y, Itoh Y (2016) Effect of Bolt-Hole Position Errors on the Strength of Bearing-Type Multi-Row Bolted Connection of FRP Composite Members. J Civil Environ Eng 6: 239. doi:10.4172/2165-784X.1000239

E_{11} (MPa)	E_{22} (MPa)	E_{33} (MPa)	v_{12}	v_{13}	v_{23}	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
26000	6000	6000	0.3	0.3	0.49	3120	3120	2000
X_T (MPa)	X_C (MPa)	Y_T (MPa)	Y_C (MPa)	Z_T (MPa)	Z_C (MPa)	S_{12} (MPa)	S_{13} (MPa)	S_{23} (MPa)
500	300	22.5	60	22.5	60	45	45	30

Table 2: Material properties of FRP unidirectional lamina [17].

Component	E (GPa)	v	$R_{0.01}$ (MPa)	f_y (MPa)	f_u (MPa)	n
Plate	200	0.3	125	205	520	6
Bolt	200	0.3	250	450	700	5

Table 3: Material properties of stainless steel.

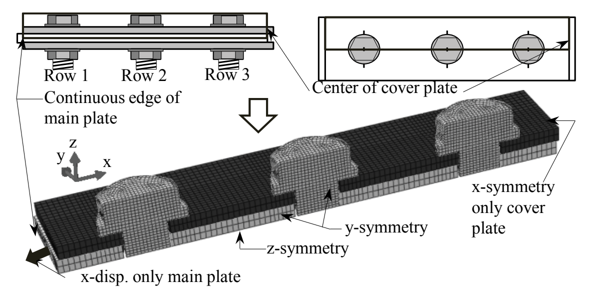


Figure 2: Finite element model.

to model the stacking sequence. The element size was determined by examining several different meshes with different mesh sizes. The total number of elements in the model shown in Figure 2 is 20343 although it may vary depending on the analytical case. Surface based contact definition is employed where different parts may contact each other. In the contact definition, the Coulomb friction model with a frictional coefficient of 0.2 is used [19,20]. Finger-tighten torque that is equivalent to an axial pre-tension force of 500 N is assumed and applied to the bolts. The position of bolt hole is changed only in cover plates.

Progressive damage analysis

The progressive damage analysis consists of stress analysis, failure criteria and material property degradation. Two principal failure criteria are considered: a) fiber failure and b) matrix failure. The failure criteria are expressed by Eqs. (2) to (4) [14].

a) Fiber failure criterion

For fiber tension $(\hat{\sigma} \geq 0)$

$$F_{ft} = \left(\frac{\hat{\sigma}_{11}}{X_T}\right)^2 + \frac{\dfrac{\hat{\tau}_{12}^2}{2G_{12}^2} + \dfrac{3}{4}\alpha\hat{\tau}_{12}^4}{\dfrac{S_{12}^2}{2G_{12}^2} + \dfrac{3}{4}\alpha S_{12}^4} + \frac{\dfrac{\hat{\tau}_{13}^2}{2G_{13}^2} + \dfrac{3}{4}\alpha\hat{\tau}_{13}^4}{\dfrac{S_{13}^2}{2G_{13}^2} + \dfrac{3}{4}\alpha S_{13}^4} \tag{2}$$

For fiber compression $(\hat{\sigma} < 0)$

$$F_{ft} = \left(\frac{\hat{\sigma}_{11}}{X_C}\right)^2 \tag{3}$$

where, X_T is tensile strength and X_C is compressive strength in the fiber direction, S_{ij} and G_{ij} are shear strength and shear modulus in the *ij* plane, respectively, α is a parameter representing the nonlinear relationship of the shear strain and shear stress, the value 1.9×10^{-6} is used, $\hat{\sigma}_{ii}$ is the *ij* components of effective stress defined as $\hat{\sigma}_{ii} = \sigma_i/(1-d_I)$, and $\hat{\tau}_{ij}$ is the *ij* components of effective shear stress defined as $\hat{\tau}_{ij} = \tau_j/(1-d_I)$. d_I is the damage index with respect to the failure mode *I*. Detailed description can be found in Ref [14].

b) Matrix failure criterion

$$F_m = \left(\frac{\hat{\sigma}_{22}}{Y}\right)^2 - \frac{\hat{\sigma}_{22}\hat{\sigma}_{33}}{YZ} + \left(\frac{\hat{\sigma}_{33}}{Z}\right)^2 + \frac{\dfrac{\hat{\tau}_{12}^2}{2G_{12}^2} + \dfrac{3}{4}\alpha\hat{\tau}_{12}^4}{\dfrac{S_{12}^2}{2G_{12}^2} + \dfrac{3}{4}\alpha S_{12}^4} + \frac{\dfrac{\hat{\tau}_{13}^2}{2G_{13}^2} + \dfrac{3}{4}\alpha\hat{\tau}_{13}^4}{\dfrac{S_{13}^2}{2G_{13}^2} + \dfrac{3}{4}\alpha S_{13}^4} + \frac{\dfrac{\hat{\tau}_{23}^2}{2G_{23}^2} + \dfrac{3}{4}\alpha\hat{\tau}_{23}^4}{\dfrac{S_{23}^2}{2G_{23}^2} + \dfrac{3}{4}\alpha S_{23}^4} \tag{4}$$

where

$$Y = \begin{cases} Y_T & \text{for } \sigma_{22} \geq 0 \\ Y_C & \text{otherwise} \end{cases} \quad \text{and} \quad Z = \begin{cases} Z_T & \text{for } \sigma_{33} \geq 0 \\ Z_C & \text{otherwise} \end{cases}$$

Y_T and Z_T denote tensile strengths, and Y_C and Z_C denote compressive strengths in the two perpendicular directions to fiber.

Once a failure criterion reaches 1.0, further loading will cause degradation of material stiffness coefficients. The stiffness coefficients are reduced diagonal components of stiffness matrix as proposed by Matzenmiller et al. [21]. The stiffness coefficients are controlled by the fiber damage index and matrix damage index that have a value between zero to one. The stiffness properties are gradually decreased after the failure of the material to keep constant stress until 95% damage. The stiffness is then considered to be zero at the 95% of damage. This progressive damage model is implemented through a subroutine UMAT in Abaqus. The model is illustrated in Ref [14] in detail.

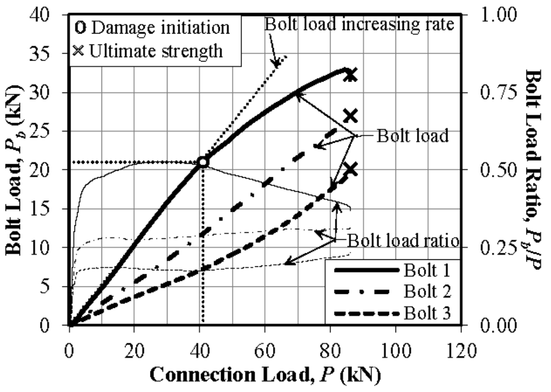
Results and Discussion

Progressive damage analysis is performed of the two, three, and four-row bolted connections with different bolt-hole positions. The results are discussed in the following sections.

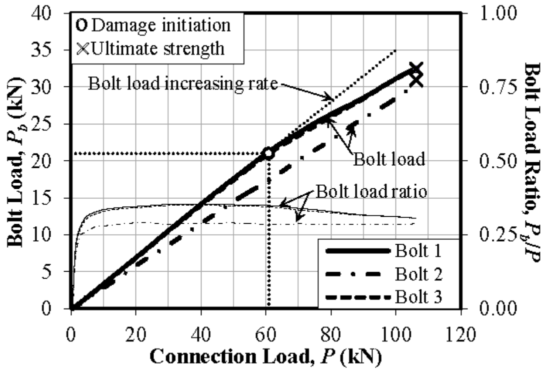
Load distribution

Figure 3 shows the load distribution among the bolts of the three-row bolted connections with steel and FRP cover plates where there is no error in bolt-hole positions. For the better understanding of the load distribution among the bolts, load of the bolts is shown by the thicker line and bolt load ratios are shown by the thinner line in the figure. The bolt load ratio is defined as a ratio of a bolt load, P_b, to the connection load, *P*. All bolts in the connections begin to carry load at the same time. In the connection with steel cover plates, every bolt carries different loads, where the first bolt takes a larger load than other bolts and the load that each transfer successively reduces with the increase the bolt number. However, in the connection with FRP cover plates, the first and last bolts carry the same load which is larger than that of the intermediate bolt. In this study, the closest and farthest bolts to the end of a main plate are designated as the last and first bolts, respectively.

In the Figure 3, the load increasing rate of the largest bolt load in the connections within the elastic limit is indicated by using a dotted line. In the connection with steel cover plates, the first bolt has the larger load



(a) Three-row bolted connection with steel cover plates.



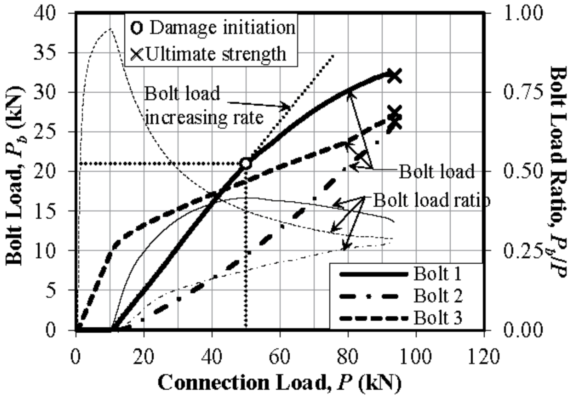
(b) Three-row bolted connection with FRP cover plates.

Figure 3: Load distribution among the bolts with a perfect bolt-hole position.

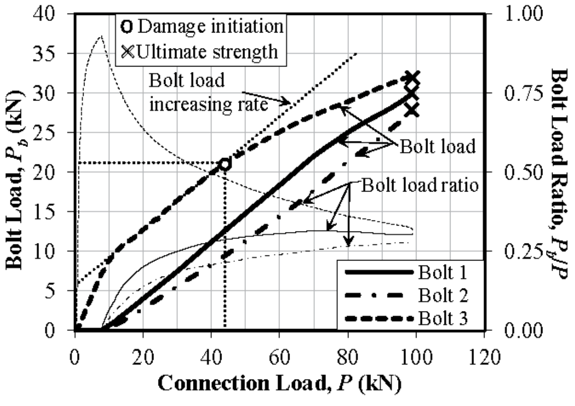
increasing rate and reaches earlier at the damage initiation stage than the other bolts and then the bolt starts shed the load to the others bolts. The damage initiation strength is defined as a load of the connection at which the load increasing rate of the largest bolt load reduces with the connection load due to the damage of the hole. As can be seen in Figure 3, the damage begins at the bolt load about 21 kN where cover plates are steel or FRP. The first bolt also fails at first in the connection. However, the first and last bolts have the larger load increasing rate then the intermediate bolt of the connection with FRP cover plates and reach at a time to those stages. The load of intermediate bolt is not larger different with the first and last bolts. It means that the load distribution among the bolts of the connection with FRP cover plates is more uniform than the connection with steel cover plates. Therefore, the connection with the FRP cover plates carries a larger load about 23% than that with steel cover plates [14]. The same results are also obtained in the two and four-row bolted connections. It indicates that the strength of a connection is affected by the load distribution among the bolts. A connection will be tolerated the maximum load when the load distribution among the bolts is uniform.

The load distribution among the bolts depends on the number of bolt rows, and the stiffness of the cover plate. However, when there are errors in bolt-hole positions, the load distribution among bolt rows is affected significantly. Figure 4 shows the load distribution among the bolts of the three-row bolted connection with position errors in the first and second holes of the cover plates along to the loading direction. The bolt-hole position error is illustrated by the Figure 5. It is observed that the last bolt of the connection contact with the cover plates and the main plate and begins to carry the load, and the other bolts are not in contact with the cover plates. The first and second bolts also begin to carry loads at the connection load of about 10 kN. After that the load increasing rates of bolt loads within the elastic limit of the material do not change, but the bolt load ratio is changed with the change of connection load. Therefore, the connection with steel cover plates, the first bolt picks up the largest load and reaches the damage initiation stage earlier than the other bolts. However, in the connection with FRP cover plates, the last bolt keeps the largest load and reaches the damage initiation stage first because the load increasing rates of the first and last bolts are the same after all bolts in contact with cover plates. It can also be observed that the connection with steel cover plates shows a larger ultimate load 8.8% when compared to the strength of that with bolt-hole positions perfectly aligned (Figures 3 and 4), although the ultimate strength of the connection with FRP cover plates is decreased to about 7%. It is because the load distribution among the bolts becomes more uniform for the connection with steel cover plates and less uniform for the connection with FRP cover plates due to the bolt-hole errors when compared that with a perfect bolt hole aligned.

Based on the observation above, the strength of a connection increases when the bolt with a lower load increasing rate in the connection begins to carry load early and all the bolts reach almost the



(a) Three-row bolted connection with steel cover plates.



(b) Three-row bolted connection with FRP cover plates.

Figure 4: Load distribution among the bolts with the bolt-hole position error.

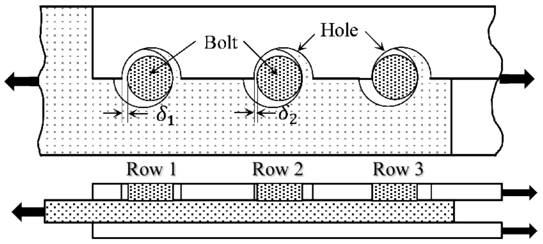


Figure 5: Three-row bolted connection with bolt-hole position error.

same time at the ultimate strength of the connection and failed at a time. On the other hand, the strength of a connection decreases when the bolt with a larger load increasing rate in the connection begins to carry load early and the bolts are failed in different interval of the connection load.

Strength

The damage initiation strength and ultimate strength of the connections are determined for each connection. These strengths of 50 connections with bolt-hole position errors are summarized in Table 4. Table 4 also shows the strengths of the connections with perfect alignment of bolt holes.

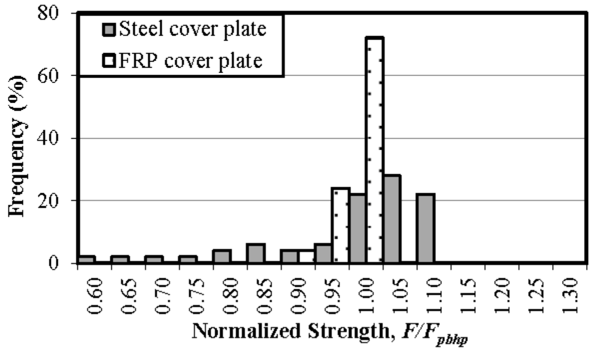
Table 4 shows that the effect of bolt-hole error on the damage initiation strength is significant for the connection with either steel or FRP cover plates. In comparison, the variations of the strength are larger for the connections with steel cover plates than those with FRP cover plates. The coefficients of variation of the damage initiation strength for two, three, and four-row bolted connections are 20.5, 25.0, and 26.7% for steel cover plates and 14.9, 18.9, and 18.7% for FRP cover plates, respectively. The average damage initiation strength is about 7% lower for steel cover plates and about 20% lower for FRP cover plates than that with bolt-hole position perfectly aligned. The connection with FRP cover plates shows the non-uniform load distribution a larger number of cases due to the error in the first and last bolt hole. Therefore, the average damage initiation strength is decreased more for the connection with FRP cover plates than that with steel cover plates.

From Table 4, it can be observed that the connections with steel cover plates are more sensitive to the bolt-hole position errors than those with FRP cover plates. The ultimate strength of the two, three, and four-row bolted connections with steel cover plates increases by about 8, 21, and 29% and decreases by about 46, 43, and 34%, respectively for the bolt-hole position errors. Whereas the connection with FRP cover plates of the two-row bolted connections, the strength does not increase, but decreases by about 14%. For the three and four-row bolted connections, the strength increases by about 2.5 and 5% and decreases by 18 and 17%, respectively. The variation of the strengths is larger for the connections with steel cover plates than those with FRP cover plates. The coefficients of variation for the ultimate strengths are less than 6% for the connections with FRP cover plates. While they are greater than 13% for the connections with steel cover plates. The average ultimate strength is about 4% lower than that of a connection with bolt-hole position perfectly aligned for any type of connections examined in this study.

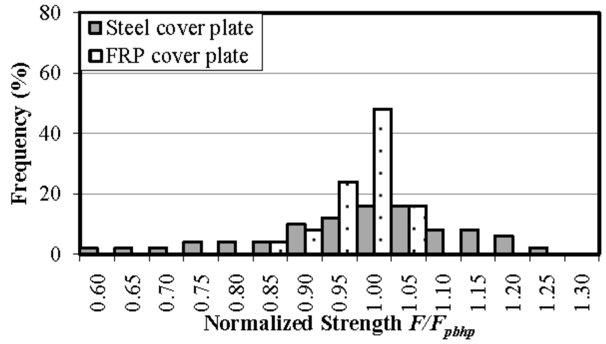
To show the effect of bolt-hole position error on the ultimate strength of connections, F, the strengths are normalized by the strength of a connection with perfect bolt-hole position, F_{pbhp}. Figure 6 shows the frequency distribution of the normalized strength of the connections. The frequency is shown in terms of percentage. The interval of the normalized strength is set to 0.05. It can be observed that the strengths of the connections with steel cover plates have spread in a wider range than those with FRP cover plates. The frequencies are larger around the normalized strength of 1.0 for the connections with steel and FRP cover plates. It is because the bolt-hole position errors are normally distributed.

Statistical test

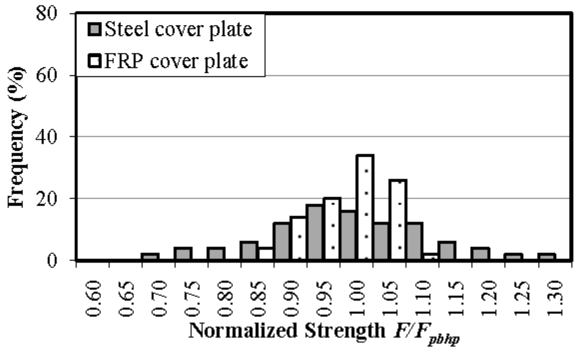
The statistical natures of the strength of bolted connections with different bolt-hole position are examined by using Latin hypercube sampling in the previous section. In this section, the distribution type and its statistical parameters are evaluated based on the results from the numerical analysis. For verifying the distribution type, for goodness of fit tests, namely Kolmogorov-Smirnov (K-S) and Chi square (χ^2)



(a) Two-row bolted connections



(b) Three-row bolted connections

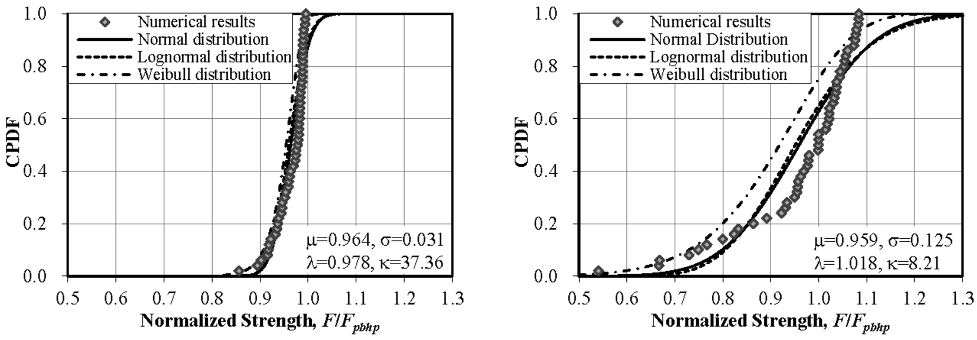


(c) Four-row bolted connections

Figure 6: Frequency distribution of the ultimate strength.

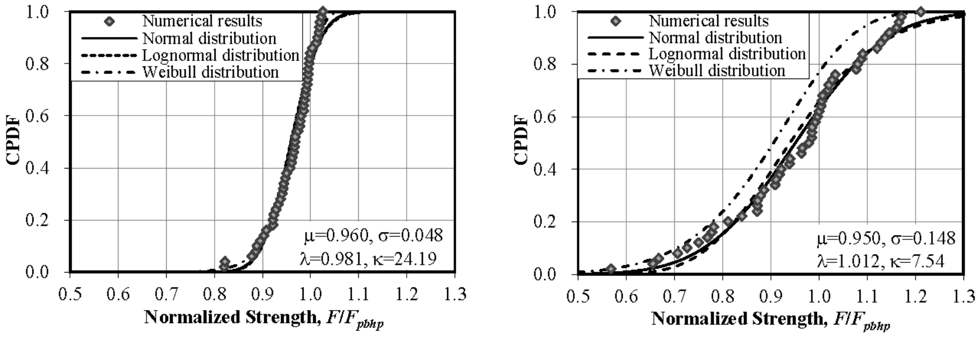
Connection		Steel cover plates						FRP cover plates					
		Perfect (kN)	Average (kN)	Max. (kN)	Min. (kN)	STDV (kN)	COV (%)	Perfect (kN)	Average (kN)	Max. (kN)	Min. (kN)	STDV (kN)	COV (%)
Damage strength	2-Row	35.8	33.8	44.5	23.0	6.7	20.5	45.6	38.1	45.6	23.3	5.7	14.9
	3-Row	41.7	39.8	62.3	23.3	10.2	25.0	64.6	51.3	66.8	29.8	9.68	18.9
	4-Row	48.5	45.0	78.5	23.7	12.0	26.7	76.5	62.0	88.0	36.8	11.6	18.7
Ultimate strength	2-Row	66.9	64.2	72.5	36.2	8.4	13.0	72.8	70.2	72.4	62.3	2.3	3.2
	3-Row	86.1	81.9	104.3	49.0	12.8	15.6	106.3	102.1	109.0	86.3	5.10	5.0
	4-Row	99.9	96.3	128.7	66.2	13.4	13.9	134.8	129.5	142.0	112.3	7.7	5.9

Table 4: Strength of the connections.



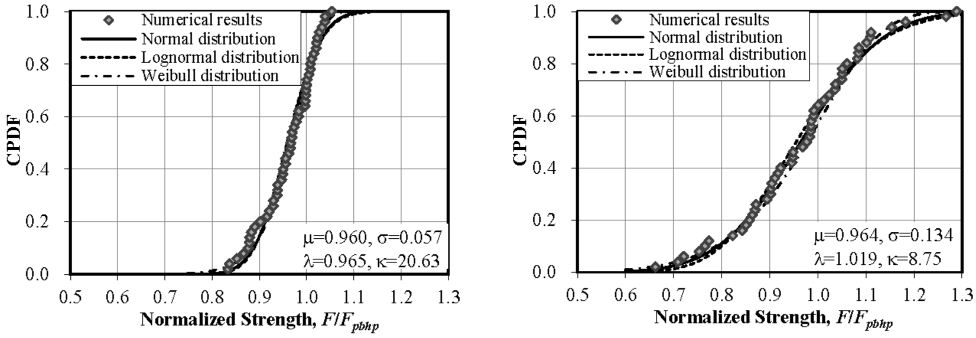
(a) Two-row bolted connections with FRP cover plates

(b) Two-row bolted connections with steel cover plates



(c) Three-row bolted connections with FRP cover plates

(d) Three-row bolted connections with steel cover plates



(e) Four-row bolted connections with FRP cover plates

(f) Four-row bolted connections with FRP cover plates

Figure 7: CPDF with normalized strength of the connections.

tests are mostly used [22]. The advantage of the K-S test over the χ^2 test is that it is not necessary to divide the data into intervals, thus the error or judgment associated with the number of size of the interval is avoided. Therefore, the K-S test is conducted in this study. In the tests for goodness of fit, normal, lognormal, and Weibull distributions are examined.

Figure 7 shows CPDFs with the normalized strength of the two- to four-row bolted connections with FRP and steel cover plates. The statistical identified parameters: mean, μ, standard deviation, σ, scale factor, λ and shape factor, κ, for those distributions are also shown in the figure. In the K-S test, maximum deviations, D_{max}, of the CPDFs between the numerical results and the distributions are calculated and compared with the tabular value $D_{\alpha=0.05}$. According to the K-S test, the data is a good fit with the distribution when D_{max} is less than D_α .The goodness of fit tests shows that the strength of two-row bolted connections with steel and FRP cover plates and three-row bolted connections with steel cover plates does not fit with the Weibull distribution and also the strength of two-row bolted connections with steel cover plates does not fit with the lognormal distribution, but fit the other distributions with a significant level of 0.05. However, the strength of three and four-row bolted connections with FRP cover plates and four-row bolted connections with steel cover plates fit all of the three distributions with a significant level of 0.05. The statistical tests for goodness of fit shows that the strength of two- to four-row bolted connections with steel cover plates and two-row bolted connections with FRP cover plates can be better modeled by a normal distribution, and the strength of the three and four-row bolted connections with FRP cover plates can be better modeled by a Weibull distribution with a significance level of 0.05. From the statistical models, it is found that 95% non-exceedance normalized strengths of the two, three and four-row bolted connections with FRP cover plates are 0.88, 0.87, and 0.85 and those with the steel cover plates are 0.75, 0.71, and 0.74, respectively.

Conclusions

The effect of bolt-hole position errors on the strength of multi-row bolted connections is investigated numerically. The bolt-hole position errors are considered in the bolt hole of cover plates to the loading direction. The bolt-hole position errors are assumed to be normally distributed and samples are generated by using Latin hypercube sampling. The following conclusions are made based on the numerical results.

(1) In bearing-type multi-row bolted connections, the load distribution among the bolts is not uniform for the connection with bolt-hole position perfectly aligned. The load distribution among the bolts is affected by the bolt-hole position errors. The bolt-hole position error will make a connection that the load distribution among the bolts will be either more or less uniform at the damage initiation strength or ultimate strength of the connection than that of bolt-hole position perfectly aligned. The load distribution will be more uniform when bolt-hole clearances in the first and last rows are larger than that of the intermediate row(s) for the connection with FRP cover plates. The load distribution of the connection with steel cover plates will be more uniform when the bolt-hole clearances in the intermediate and the first rows are larger than that of the last row.

(2) The effect of bolt-hole error on the damage initiation strength is significant for the connection with either steel or FRP cover plates. However, variations of the damage initiation strength are larger for the connections with steel cover plates than those with FRP cover plates. The coefficients of variation of the damage initiation strength for two, three, and four-row bolted connections are 20.5, 25.0, and 26.7% for steel cover plates and 14.9, 18.9, and 18.7% for FRP cover plates, respectively. The average damage initiation strength is about 7% lower for steel cover plates and about 20% lower for FRP cover plates than that with bolt-hole position perfectly aligned.

(3) The ultimate strength of bolted connections is also affected by the bolt-hole position errors. The strength can either increase or decrease with a larger probability to decrease. The average ultimate strength is about 4% lower than that of a connection with bolt-hole position perfectly aligned for any type of connections examined in this study. The effect of bolt-hole error of the connection on the ultimate strength is larger for the connection with steel cover plates than that with FRP cover plates. The coefficients of variation of the ultimate strength of the two, three, and four-row bolted connections with steel cover plates are 13.0, 15.6, and 13.9%, respectively, whereas those of connections with FRP cover plates are 3.2, 5.0, and 5.9%, respectively.

(4) Probability distribution of the ultimate strength due to bolt-hole position errors for the two- to four-row bolted connections with steel cover plates and two-row bolted connections with FRP cover plates can be modeled by a normal distribution, and that of the three and four-row bolted connections with FRP cover plates can be modeled by a Weibull distribution with a significance level of 0.05. Ninety five percent non-exceedance strength of the connection with FRP cover plates is about 85% of the connection with bolt positions perfectly aligned, while that of the connection with steel cover plates is about 71% of the perfect bolt position case.

References

1. Karbhari VM, Zhao L (2000) Use of composites for 21st century civil infrastructure. Compute method Appl M 185: 433-454.
2. Camanho PP, Matthews FL (1999) A progressive damage model for mechanically fastened joints in composite laminates. J Compos Matter 33: 2248-2280.
3. Hassan NK, Mohamedien MA, Rizkalla SH (1997) Multibolted joints for GFRP structural members. J Comp Constr, ASCE 1: 3-9.
4. Cooper C, Turvey GJ (1995) Effects of joint geometry and bolt torque on the structural performance of single bolt tension joints in pultruded GRP sheet material. Comps Struct 32: 217-226.
5. Ascione F, Feo L, Maceri F (2009) An experimental investigation on the bearing failure load of glass fibre/epoxy laminates. Compos Part B-Eng 40: 197-205.
6. Khashaba UA, Sebaey TA, Mahmoud FF, Selmy AI, Hamouda RM (2013) Experimental and numerical analysis of pinned-joints composite laminates: Effects of stacking sequences. J Compos Matter 47: 3353-3366.
7. Lawlor VP, McCarthy MA, Stanley WF (2005) An experimental study of bolt-hole clearance effects in double-lap, multi-bolt composite joints. Compos Part B-Eng 36: 290-305.
8. Kader MA, Kitane Y, Itoh Y (2015) Effect of cover plate stiffness on load distribution of bearing-type multi-row bolted connections for FRP composite structures. J Soc Mater Sci Japan 64.
9. Içten A, Imrek Ḧ, Cunedioğlu Y (2009) Experimental and numerical failure analysis of pinned-joints in composite materials. Compos Struct 89: 459-66.
10. Pisano AA, Fuschi P, De Domenico D (2013) Failure modes prediction of multi-pin joints FRP laminates by limit analysis. Compos Part B-Eng 46:197-206.
11. Camanho PP, Matthews FL (1997) Stress analysis and strength prediction of mechanically fastened joints in FRP: a review. Composites Part A 28(6): 529-47.
12. Thoppul SD, Finegan J, Gibson RF (2009) Mechanics of mechanically fastened joints in polymer-matrix composite structures - A review. Compos Sci Technol 69: 301-329.
13. Vasarhelyi DD, Chang WN (1965) Misalignment in bolted joints. J Struct Div, Proc Am Soc Civil Engineers 91: 1-15.
14. Kader MA, Kitane Y, Itoh Y (2015) Strength of bearing-type multi-row bolted connections of FRP composite members with varying cover plate stiffness. Elegance in Structures, Proc. IABSE Conference Nara 2015, Nara, Japan, 13-15 May 2015, Paper No. IA-33.
15. Fan WX, Qiu CT (1993) Load distribution of multi-fastener laminated composite joints. Int J Solids Struct 30: 3013-3023.
16. McKay MD, Conover WJ, Beckman RJ (1979) A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. Technometrics 21: 239-245.

17. Kishore AN, Malhotra SK, Prasad NS (2009) Failure analysis of multi-pin joints in glass fibre/epoxy composite laminates. Compos Struct 91: 266-277.
18. Dassault Systèms (2011) Abaqus 6.11 documentation.
19. Mottram JT, Lutz C, Dunscombe, GC (2004) Aspects on the behaviour of bolted joints for pultruded fibre reinforced polymer profiles, Proc. 2nd Inter. Conf. on Advanced Polymer Composites for Structural Applications in Construction (ACIC04). University of Surrey, UK, 20-22 April 2004. Woodhead Publishing Limited, Cambridge, pp. 384-391.
20. Hyer MW, Hung CL, Cooper DE (1987) Effects of pin elasticity, clearance and friction on the stresses in a pin-loaded orthotropic plate. J Compos Matter 21: 190-206.
21. Matzenmiller A, Lubliner J, Taylor RL (1995) A constitutive model for anisotropic damage in fiber-composites. Mech Mater 20: 125-152.
22. Haldar A, Mahadevan S (2000) Probability, Reliability and Statistical Methods in Engineering Design. John Wiley and Sons, Inc. New York.

This article was originally published in a special issue, **Corrosion of Steel in concrete structures** handled by Editor(s). Raja Rizwan Hussain, King Saud
University